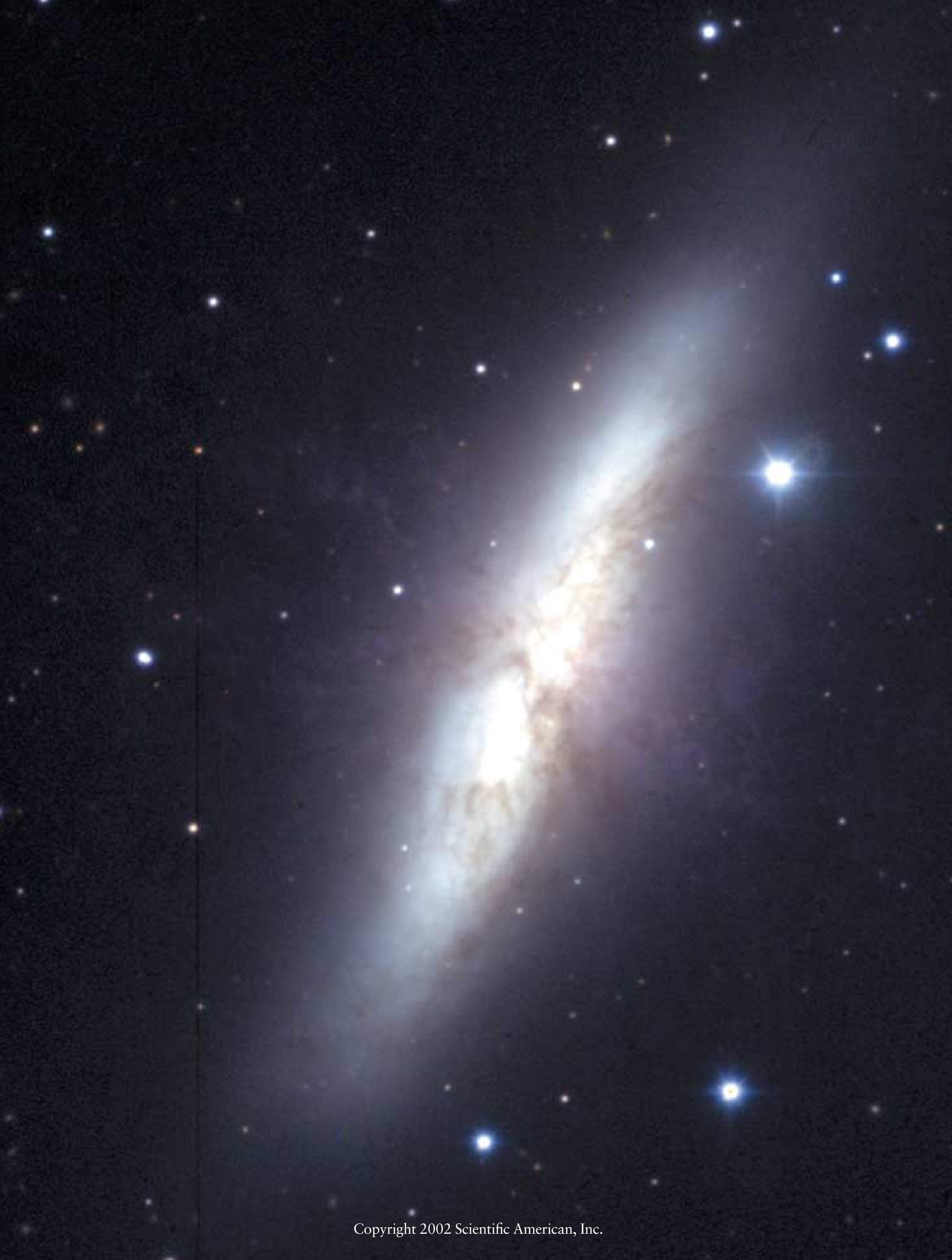

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the Cosmic Reality Check

A celestial audit suggests that astronomers' inventory of luminous bodies may soon be complete

By Günther Hasinger and Roberto Gilli

MOST OF THE LIGHT in the universe probably comes from tortured galaxies such as M82, where stars form at 10 times the rate of our Milky Way and a massive black hole may lurk at the center. These galaxies are often veiled by thick clouds of dust. Only in the past several years have astronomers appreciated their prevalence.

With each day's newspaper seems to arrive a new astronomical discovery: a new celestial body, a new physical process, a new form of matter. Will the revelations ever end? Will there ever come a day when astronomers feel confident that they have made a complete inventory of the universe? If the question is put so broadly, the answer is clearly no: astronomers already know that not everything in the universe can be seen directly, and additional surprises are inevitable. But a somewhat narrower question—will astronomers ever finish their head count of stars, galaxies and other luminous matter?—has a rather different answer. A day will indeed come when astronomers have accounted for the bulk of the light in the universe, and that day is fast approaching.

Over the years, astronomers have developed a type of quality-control check that can signal whether they have missed any important source of light. The idea is to study a phenomenon that most observers consider a nuisance: the so-called background radiation. When scientists in any discipline talk about a "background," they usually mean everything except what they are interested in. A telescope capturing the radiation from a star cannot avoid collecting light from other bodies near and far. This extraneous light serves only to reduce the precision of the desired measurement.

Those of us who study the background radiation focus our attention precisely on what our colleagues try to ignore. We first add up all the light coming from a given region of space. Then we systematically subtract the contributions from known objects such as stars, galaxies and gas clouds—collectively, the "foreground." If something is left over, some diffuse glow of indeterminate origin, we know that our census of heavenly objects must still be incomplete.

Sometimes a diffuse glow is observed when objects are very

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closely spaced and the telescope lacks sufficient angular resolution to pick them apart. Take, for example, the Milky Way, which is a blur to the naked eye. With a simple pair of binoculars, you can see that the blur consists of millions of individual points of light. At other times, a diffuse glow comes from a source that truly is diffuse, such as the zodiacal dust of our own solar system or the gaseous supernova remnants of our galaxy. Many (but by no means all) of these sources within our galaxy and nearby galaxies have been identified, so they can be considered part of the foreground. The radiation that comes from far outside our galaxy, filling the whole universe, is the cosmic background.

In the past half a decade, as the sensitivity and resolution of telescopes have improved dramatically, astronomers have accounted for more and more of the background glow. In so doing, we have discovered that our previous inventories of the universe were incomplete: for instance, we had badly underestimated the prevalence of supermassive black holes. Far from being isolated oddities, as was once thought, they are everywhere. Earlier studies had missed them because they are cloaked by prodigious quantities of dust. With these holes now unveiled, we may soon explain the background fully.

That is not to say we will have seen everything there is to see. We can no more catalogue every celestial body than a biologist can count every beetle. But just as biologists can fairly claim to know all the major types of, say, land mammals, astronomers are on the verge of identifying all the major classes of light-emitting objects.

LITTLE MORE THAN A BLUR to the naked eye, the Milky Way dissolves into 100 billion stars when viewed through a telescope. The inset shows fine detail in the constellation Ara. Similarly, the cosmic background—a subtle glow that fills the sky between the stars—used to look like a blur. In recent years, telescopes have become advanced enough to pick out individual sources of light, many of which represent new classes of galaxies.

preceding pages: PETER CHALLIS *Harvard-Smithsonian Center for Astrophysics; this page:* ROGER RESSMEYER *Corbis;* WFI/EUROPEAN SOUTHERN OBSERVATORY *(inset)*

Not a Whisper Be Lost

WHEN ASTRONOMY AFICIONADOS hear the word "background," they immediately think of the famous cosmic microwave background (CMB). This pervasive radio emission appears to have a truly diffuse origin—namely, a hot plasma that filled the universe when it was only 400,000 years old. Through the expansion of the universe, this radiation is today observed at a peak wavelength of about one millimeter, corresponding to a temperature of 2.7 kelvins. The study of the spectrum and distribution of the CMB has provided compelling evidence for the big bang theory.

Yet the CMB is only part of the story. The whole electromagnetic background is actually a mixture of components, each of which dominates a particular range of wavelengths. Besides the CMB are the lesser-known cosmic x-ray background (CXB), cosmic infrared background (CIB) and cosmic optical background (COB).

The precise measurement of these components is one of the most trying tasks in observational astronomy. Conceptually it seems so simple: look at the sky to measure the total signal and then subtract all the known sources between Earth and the deep universe (the foreground): the noise of the detectors, the signals

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from within our solar system, the emission from the rest of the galaxy, and so forth. In addition, one has to correct for any foreground attenuation of the background signal.

Performing all these subtractions with sufficient precision, though, is tricky; subtraction is an operation that amplifies error. In certain wavelength bands, observers are lucky that the background is the brightest emission in the sky, but in other bands they have to extract a cosmic whisper from a foreground roar. Most often the limiting factor is the accuracy with which astronomers know the foreground emission. They try to skirt this problem by concentrating on regions of the sky that are utterly devoid of stars and other known foregrounds—the more boring, the better. Despite the obstacles, observers have now determined the cosmic background spectrum with quite high precision over a broad range of the spectrum [*see illustration on page 67*].

The x-ray component, discovered in 1962, has a characteristic hump at about 30 kiloelectron-volts—corresponding roughly to the wavelength used for medical x-rays—and a long tail toward higher energies, including gamma rays. Below about 1 keV, and superposed on this continuum, are a number of atomic emission lines that appear to be the fingerprint of a gas heated to several million kelvins and most likely located inside or around our galaxy.

In the 1970s the first x-ray satellites, such as UHURU, ARIEL V and HEAO-1, showed the higher-energy x-radiation to be spread uniformly over the sky. Thus, its origin has to be mainly extragalactic: if it came from our solar system or galaxy, the brightness would be strongly skewed in certain directions corresponding to the plane of the planets or galactic disk. Gamma-ray satellites such as SAS-3, COS-B and the Compton Gamma Ray Observatory have found a similar uniformity at still higher energies.

Whereas the CMB and CXB dominate the sky in their respective bands, the other cosmic background components account for only a small fraction of the radiation in their respective wavelength bands. A few years ago several groups independently detected the far-infrared background signal in the high-frequency tail of the CMB [see "Glow in the Dark," by George Musser; SCIENTIFIC AMERICAN, March 1998]. In the near- to mid-infrared range, the bright zodiacal light obscures the background, so astronomers have generally resorted to interpolating measurements from other wavelength bands. They have also derived upper limits from observations of high-energy gamma rays: too thick a haze of infrared photons would interfere with the propagation of gamma rays. Only in the past two years have observers made direct measurements at infrared wavelengths.

In the optical and ultraviolet, the first direct background measurements were announced last December by Rebecca A. Bernstein of the University of Michigan and her colleagues. Before their work, astronomers had relied on constraints derived by summing up the light from the faintest galaxies seen by the Hubble Space Telescope. In the extreme ultraviolet, the background is obscured by the interstellar medium, so the background level can be estimated only by interpolating between the ultraviolet and x-ray measurements.

Hidden in the Background

TO USE THE BACKGROUND radiation as a quality-control check, astronomers have had to develop ways to compare what is measured with what is expected. That is no easy task. The background represents a tangled mixture of light from various classes of astronomical objects. Starlight, which is produced by thermonuclear fusion, is mainly confined to near-infrared, optical and ultraviolet wavelengths. Quasars and other active galactic nuclei (AGN), whose black holes suck in matter and efficiently convert its gravitational energy into radiation, shine in a very broad band, from radio to gamma wavelengths. Clouds of dust absorb optical, ultraviolet and x-ray light and reradiate the energy in the far-infrared. To complicate matters further, the background blends together light from objects at vastly different cosmic distances and evolutionary stages.

One strategy is to conduct intensive surveys of the sky—to make observations with the highest possible resolution and sensitivity and thereby get a fix on the specific sources of the background. By comparing the findings made at different wavelengths, we can determine what kind of objects these sources are. This direct approach, however, can achieve the requisite precision only for relatively bright objects in very limited areas of the sky. For the broader picture, we turn to a second technique known as population synthesis: calculate the expected emission from possible combinations of objects, compare this prediction with the background measurements, and continue trying different combinations until one seems to fit.

Because the CXB was the first known background, it has been studied more than the other background components. The most basic question—does the CXB come from unresolved sources or a hitherto unknown type of diffuse gas?—was debated for three decades [see "The Origin of the Cosmic X-ray Background," by Bruce Margon; SCIENTIFIC AMERICAN, Jan-

THE AUTHORS

GÜNTHER HASINGER and ***ROBERTO GILLI*** began to work together on the x-ray background radiation at the Astrophysical Institute in Potsdam, Germany, where Hasinger was the director and Gilli did some of the work for his Ph.D. Hasinger, now a director at the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, is primarily an observer. Gilli, now at Arcetri Observatory in Florence, Italy, is primarily a modeler. Hasinger very nearly became a rock musician instead of an astronomer. He played bass guitar and traverse flute and was recording his first album when his mother insisted that he enroll at the University of Munich, lest she lose child-support benefits. He still jams occasionally. Gilli, for his part, was steered away from a career in soccer.

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uary 1983]. In the 1990s an indirect line of argument finally settled the issue. If the CXB comes from hot intergalactic gas, the gas should also act as a screen that distorts our view of the cosmic microwave background. The spectrum of the CMB would then deviate from that of a perfect blackbody. Yet CMB observations, notably by the Cosmic Background Explorer satellite, saw no such deviation. Therefore, only a small fraction of the x-ray background can come from such gas; cooler gas might contribute, but for the most part, the CXB must represent unidentified discrete sources.

But what could these sources be? The first intensive surveys to answer this question were performed in the early 1980s with the Einstein x-ray satellite (HEAO-2) by Riccardo Giacconi, the discoverer of the CXB, and others. They resolved about a fifth of the x-ray background into discrete sources, including quasars. The ROSAT satellite followed up this work. In 1984 a group of scientists consisting of Giacconi, Maarten Schmidt (the discoverer of quasars), Joachim Trümper (the father of ROSAT) and one of us (Hasinger) met at the Max Planck Institute for Extraterrestial Physics in Garching, Germany, to start planning for deep surveys with that satellite. After the ROSAT launch in 1990, the surveys became a major enterprise lasting over a decade and involving a large number of co-workers, more than we could possibly list here.

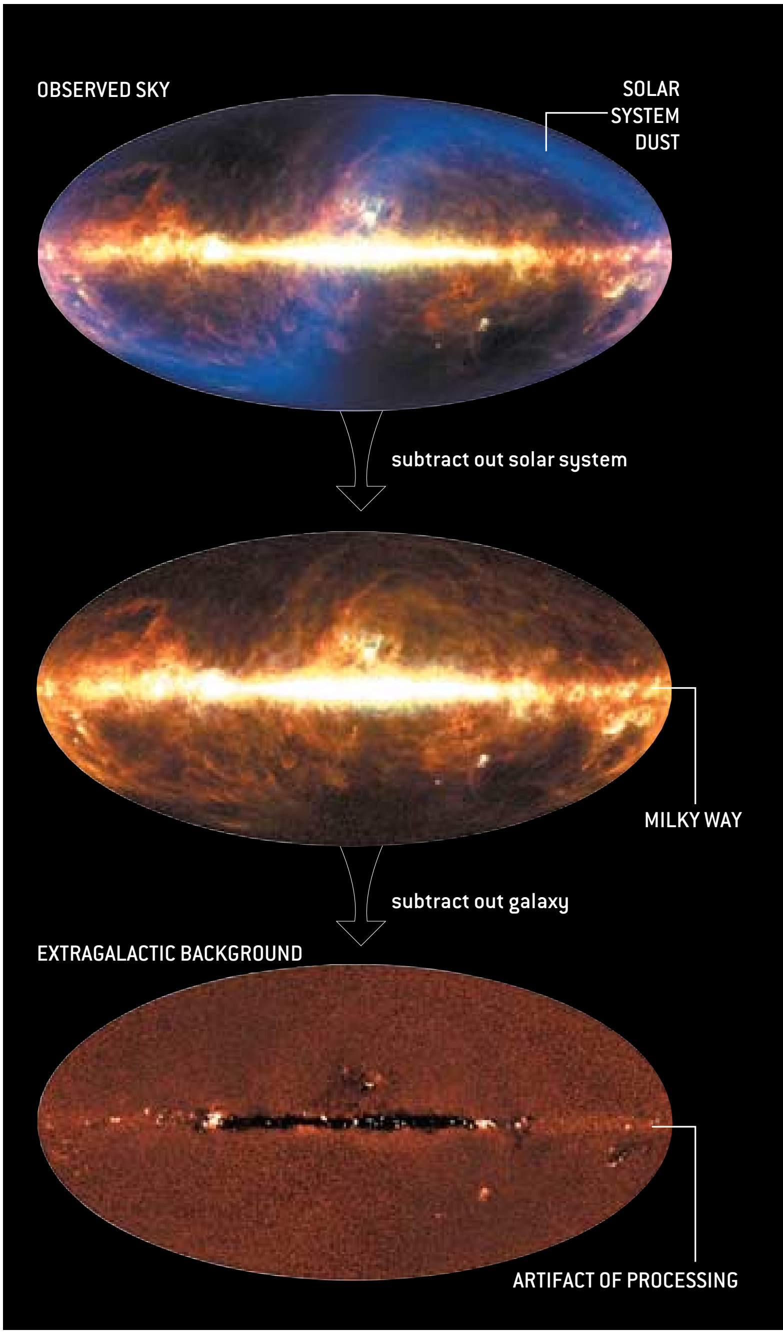
The ROSAT Deep Surveys of the so-called Lockman Hole—an area close to the Big Dipper that is almost free from foreground absorption—are among the longest and deepest x-ray-plus-optical observations ever performed. They have resolved 80 percent of the x-ray background at energies of less than 2 keV, a range that astronomers call soft x-rays. The main bottleneck has been making the optical identifications. We have to look for counterparts of the x-ray sources on deep optical images, and often they are extremely faint. Then we have to obtain their spectra, which reveal the properties of the objects as well as their redshift, a measure of distance. This work would not be possible without the giant Keck telescope, but even its 10-meter mirror has trouble collecting enough light to measure the spectra of the faintest optical counterparts.

About 80 percent of the ROSAT sources have turned out to be active galactic nuclei of various kinds—mostly luminous quasars and so-called Seyfert-1 galaxies. The broad emission lines in the spectra of these AGNs indicate that we have a clear view into their innermost regions, where the monstrous black holes are gorging themselves.

Wallowing in Dust

THE REST OF THE AGNs, however, show only narrow emission lines or no emission lines at all—suggesting that gas and dust block our view of their central black holes. They are classified as type 2 quasars or Seyfert-2 galaxies. The existence of a second type makes sense in the framework of the "unified model" for AGNs. Proposed in the mid-1980s, the unified model posits that all AGNs contain not only a central black hole but also a torus of gas and dust. Depending on how this torus is oriented, it can hide the black hole. The model has since been updated, but the basic prediction has stayed the same: we perceive either an unobscured (type 1) or an obscured (type 2) AGN.

Although these soft-x-ray surveys showed that AGNs are the dominant sources of the x-ray background, an apparent paradox emerged as astronomers began to employ their second strategy to understand the background—namely, population synthesis. When astronomers added together the spectra of dif-



LIKE STRIPPING OFF LAYERS OF PAINT to expose the wall underneath, measuring the cosmic background involves taking an image of the sky, then subtracting light from known objects and seeing what is left. In these images, which combine the far-infrared wavelengths of 60 (*blue*), 100 (*green*) and 240 microns (*red*), the sky is projected so that the Milky Way runs across its center; the plane of the planets has an S shape.

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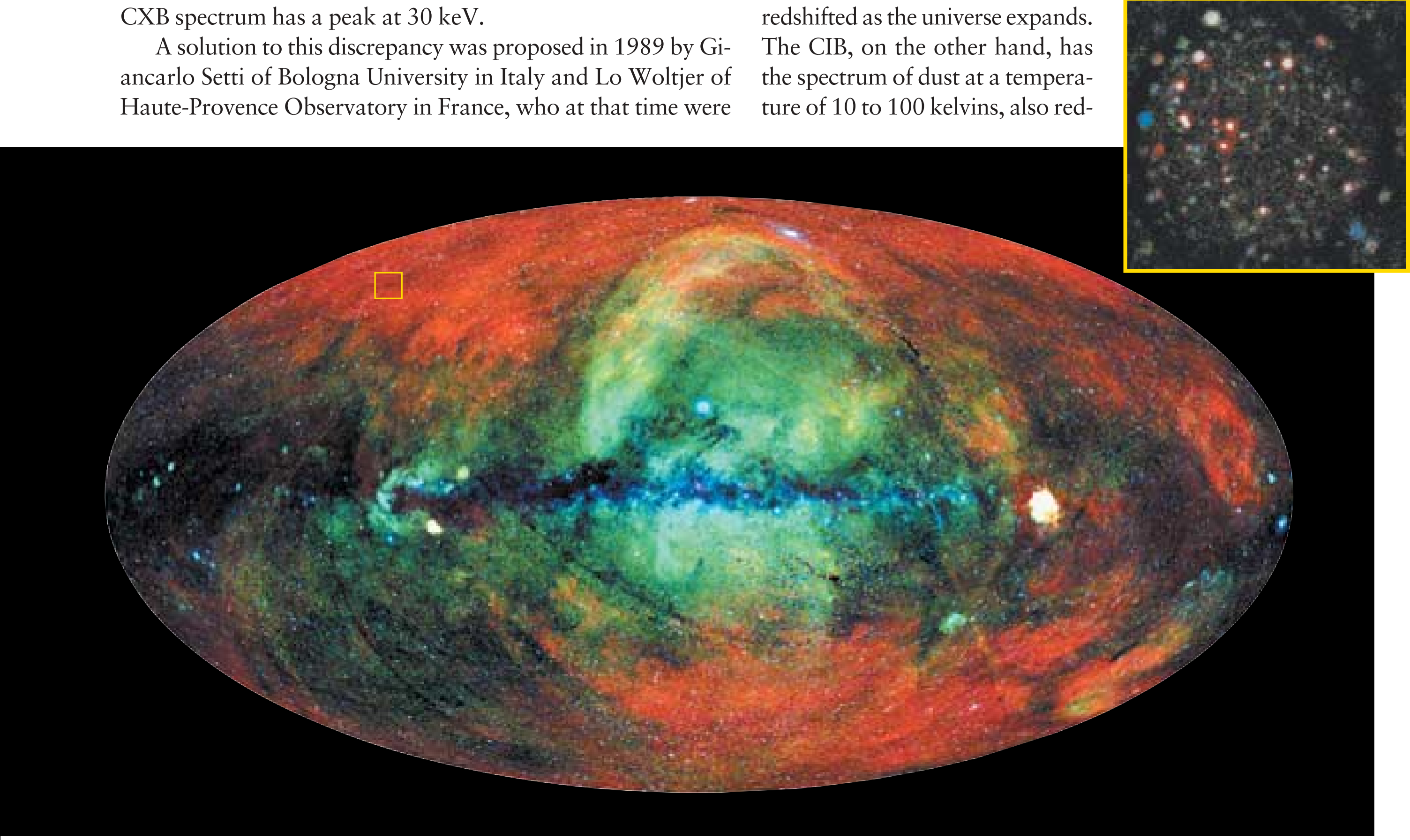
ferent types of AGNs according to their observed proportions, the result should have equaled the spectrum of the CXB. It did not. AGN spectra have a flat or bowl-like shape, whereas the CXB spectrum has a peak at 30 keV.



IN AN X-RAY IMAGE OF THE SKY, the cosmic background radiation is easy to see: it is the haze in areas away from the Milky Way (*horizontal band*). The ROSAT satellite, which made this image, also took a detailed look at the Lockman Hole, a patch of sky where the background is especially visible (*inset*). The box shows its approximate location. The colors represent high- (*blue*), medium- (*green*) and low-energy (*red*) x-rays.

A solution to this discrepancy was proposed in 1989 by Giancarlo Setti of Bologna University in Italy and Lo Woltjer of Haute-Provence Observatory in France, who at that time were working together at the European Southern Observatory in Garching. They hypothesized that population-synthesis modeling had not added the AGNs in their correct proportions. Contrary to what people had thought, most sources of the x-ray background could be type 2 AGNs. Higher-energy (so-called hard) x-rays can penetrate the dust and gas around these black holes, whereas the soft x-rays are absorbed. In this way, the overall CXB spectrum would differ from that of bright AGNs.

Picking up on this idea, population-synthesis modelers sought the right mixture of type 1 and type 2 AGNs that would explain the CXB spectrum, taking into account how these objects might evolve over time. As shown in 1995 by Andrea Comastri, then at the Max Planck Institute for Extraterrestrial Physics, and his co-workers, such models can reproduce the spectrum up to about 300 keV if the vast majority—80 to 90 percent—of the energy produced by black holes is veiled by thick clouds of gas and dust. If so, these beasts were 100 times more abundant in the early universe than today—a figure consistent with their forming in almost all galaxies. They might have gone unnoticed were it not for the cosmic x-ray background.

A related paradox concerns the optical and infrared backgrounds (the COB and CIB, respectively). The COB is most likely the summed emission of stars, redshifted as the universe expands. The CIB, on the other hand, has the spectrum of dust at a temperature of 10 to 100 kelvins, also redshifted. The energy represented by the dust emission must ultimately originate in stars and AGNs. Yet the CIB is as bright as or brighter than the COB. It is as though the moon (which merely reflects sunlight) were brighter than the sun (the source of that light). The logical resolution of this paradox, like that of the x-ray paradox, is that a substantial fraction of radiation sources in the universe is shrouded by gas and dust.

To confirm these inferences, astronomers have been studying the background radiation at wavelengths that would be unaffected by any obscuring material—namely, hard x-rays. This potent radiation passes through dust as though the dust were not even there. The two great new x-ray observatories now in orbit, the Chandra X-ray Observatory (with superb angular resolution) and XMM-Newton (with a large telescope area), have extended the band covered by ROSAT to substantially higher energies, up to 10 keV, though not yet to the peak of the x-ray background. The most sensitive x-ray surveys to date have been performed with Chandra in two sky areas, the Chandra Deep Field South and the Hubble Deep Field North, by the groups led by Giacconi, who is now at Johns Hopkins University, and by Gordon

opposite page: MICHAEL HAUSER *Space Telescope Science Institute* AND NASA;
this page: MAX PLANCK INSTITUTE FOR EXTRATERRESTRIAL PHYSICS

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DISTANT AND DUSTY GALAXIES, the missing link in understanding the cosmic background, show up in the famous Hubble Deep Field (*above*) and a Chandra x-ray image of the same region (*inset*). Comparing the two images allows astronomers to identify these objects. Many are powered by supermassive black holes.

NASA/PSU/G. GARMIRE, N. BRANDT ET AL.

P. Garmire of Pennsylvania State University. These surveys have resolved at least 80 percent of the hard x-ray background.

The optical matchup work has just started. So far the sources are a mixture of type 1 and type 2 AGNs, in excellent agreement with the models. Interestingly, about 10 percent of the x-ray sources discovered by Chandra are very faint galaxies—presumably normal galaxies that contain no AGNs. Their x-ray emission is associated mainly with gas heated by star formation.

Your Friendly Neighborhood ULIRG

THE TWO MAIN STRATEGIES used to study the background leave something to be desired. The intensive surveys push technology to and beyond its limits, and population synthesis is rather abstract. Astronomers have therefore developed a third strategy: scour the nearby universe for counterparts to the distant type 2 galaxies.

They have found their answer in the galaxy NGC 6240. It is one of the black sheep of the Milky Way's neighborhood—a member of an exotic class known as ultraluminous infrared galaxies (ULIRGs). Such galaxies emit most of their total energy output in the far-infrared, a telltale sign that they are saturated with dust. Because dust consists of heavy chemical elements that are synthesized in stars and scattered through space when those stars die, prodigious amounts of dust imply prodigious star formation. Whereas the Milky Way is making a few new stars a year, NGC 6240 must be churning out hundreds. Not only is NGC 6240 wracked by star formation, it is cursed with one of the most voracious black holes in the nearby universe.

The overall spectrum of NGC 6240 has the same shape as that of the cosmic background. It contains all the ingredients we need to explain the background, although we still need to mix them in the right proportions.

Seeing what NGC 6240 looks like, astronomers have realized that the unexpected prevalence of type 2 AGNs in the early universe has a natural explanation: the AGNs were accompanied by bursts of star formation. Stars spewed dust, which hides the holes from our view. Indeed, an accumulating body of evidence indicates that star formation and black-hole feeding were much more common in the past than today. The two processes seem to have hit their peak at roughly the same era in cosmic history.

Why do AGNs and starbursts occur hand in hand? No one yet knows. It seems quite likely that the two processes have the same underlying cause: galaxy collisions, which cause gas to spiral toward the center of the galaxy, whereupon it either forms stars or falls into the hole. Nearly all ULIRGs, including NGC 6240, show signs of having undergone a collision with another galaxy. On the other hand, not all AGNs seem to be associated with major collisions.

Many researchers think the connection between AGNs and starbursts may be much tighter than merely having a common source of fuel. Black holes could directly stoke the fires of star formation, or stars could help funnel material into the hole. Stars and supermassive holes might even be symbiotic, unable to exist without one another. Such connections might account for the correlation between the properties of galaxies and their central holes [see "The Hole Shebang," by George Musser; SCIENTIFIC AMERICAN, October 2000].

Fortified by studies of NGC 6240 and its ilk, astronomers have used population synthesis to see whether AGNs and starbursts could explain not just the x-ray background but also the optical and infrared backgrounds. The answer appears to be no.

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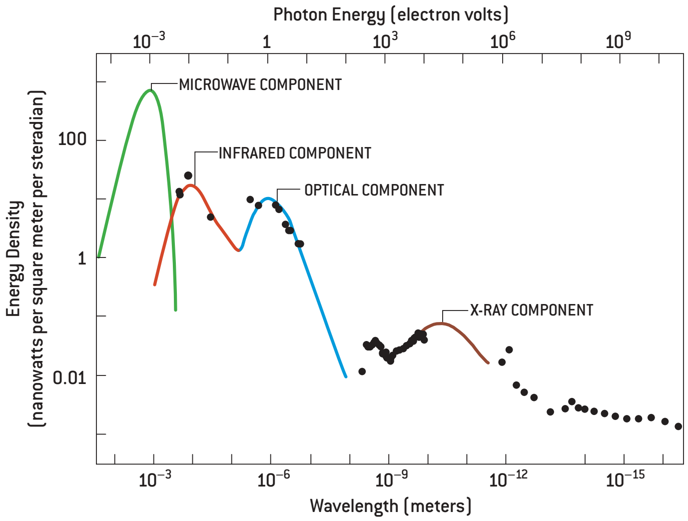
Joint observations by Chandra and the SCUBA instrument, which observes at submillimeter wavelengths between the far-infrared and radio, have failed to note much overlap. Omar Almaini of the Royal Observatory in Edinburgh, Scotland, and his collaborators estimate that up to 30 percent of the cosmic infrared background is ultimately generated by AGNs. Hasinger and his colleagues have combined XMM and Infrared Space Observatory measurements of the Lockman Hole, putting a lower limit—15 percent—on the AGN contribution to the infrared background.

Elese N. Archibald of the Joint Astronomy Center in Hilo, Hawaii, and her co-workers have explained these findings as a natural sequence of galaxy formation. In their scenario, each galaxy forms around a seed black hole of relatively low mass (10 to 1,000 solar masses). At first, starlight dominates the total output of the galaxy, because the little hole still has to grow. The hole does so exponentially by swallowing material as fast as it can. After about 500 million years, the hole is so fat—a billion solar masses—that infalling material outshines the stars. A quasar is born. After a while, this quasar has eaten all the available fuel and falls asleep until new gas falls into the center, waking it up. The hole may also merge with another of like size.

To be sure, some researchers think we may still be missing some crucial piece of the puzzle, such as galaxies that are too spread out to see directly or stars that formed before galaxies did [see "The First Stars in the Universe," by Richard B. Larson and Volker Bromm; SCIENTIFIC AMERICAN, December 2001]. Sources other than AGNs have been proposed for the very high-energy tail of the CXB. For example, a significant fraction of the gamma rays could be produced by electrons catapulted to immense speeds during the formation of the large-scale structure of the universe.



COBBLING TOGETHER observations (*dots*) at different wavelengths, astronomers have prepared a spectrum of the cosmic background. Four components (*solid curves*) are obvious; they peak at different wavelengths and represent different ways to generate light. Nearly all the background energy can now be accounted for. (A steradian is about 1/13 of a sphere.)

JOHNNY JOHNSON; SOURCE: GÜNTHER HASINGER AND ROBERTO GILLI

Further intensive surveys are needed to disentangle the various processes that contribute to the background, and future observatories—such as the Space Infrared Telescope Facility, the Herschel Far-Infrared Telescope, the Next Generation Space Telescope and the Atacama Large Millimeter Array—will be required to study some of the objects that x-ray satellites have detected. X-ray spectrometry by the planned XEUS mission could be crucial because it might be able to estimate redshifts from x-ray data alone, thereby allowing observation of objects too heavily obscured to be visible in the optical at all. Such work might finally explain the mysterious link between galaxies and the black holes at their centers, deduce which formed first, and describe how star formation relates to black-hole activity.

The Bright Night Sky

THE STUDY OF THE BACKGROUND is a classic example of how nothing in astronomy is quite what it appears to be. The mere presence of the background indicates that, despite first appearances, the night sky is not completely dark. For most of human history, the darkness of the night sky was taken for granted, and the question was why it was so. In an infinite universe filled with stars, every line of sight should eventually meet the surface of a star. The dimming of starlight with distance should be exactly canceled by the increase in the number of stars you see as you look farther out, so the night sky should appear as bright as the surface of the sun. Day and night should blend into one.

This puzzle, known as Olber's paradox, was solved in 1848 by Edgar Allan Poe. In his prose poem *Eureka,* he argued that the stars must not have had enough time to fill the universe with light. The darkness of the night sky, then, tells us that the universe has not existed forever. Not only has that hypothesis stood the test of time, it eventually proved crucial to formulating the big bang theory.

Still, the night is not pitch-black; it is pervaded by the cosmic background. Although we have made much progress in explaining it, we have much left to do. Whereas 19th-century thinkers had to explain why the night sky isn't bright, modern cosmologists must figure out why it isn't completely dark. SA

MORE TO EXPLORE

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For other papers on the background radiation, visit **http://nedwww.ipac.caltech.edu/level5/bcg_radiation.html**

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